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Inventory of MRI applications and workers exposed to MRI-related electromagnetic fields in the Netherlands

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A B S T R A C T

Objective: This study aims to characterise and quantify the population that is occupationally exposed to electromagnetic fields (EMF) from magnetic resonance imaging (MRI) devices and to identify factors that determine the probability and type of exposure.

Materials and methods: A questionnaire survey was used to collect information about scanners, procedures, historical developments and employees working with or near MRI scanners in clinical and research MRI departments in the Netherlands.

Results: Data were obtained from 145 MRI departments. A rapid increase in the use of MRI and field strength of the scanners was observed and quantified. The strongest magnets were employed by academic hospitals and research departments. Approximately 7000 individuals were reported to be working inside an MRI scanner room and were thus considered to have high probability of occupational exposure to static magnetic fields (SMF). Fifty-four per cent was exposed to SMF at least one day per month. The largest occupationally exposed group were radiographers ($n \sim 1700$). Nine per cent of the 7000 involved workers were regularly present inside a scanner room during image acquisition, when exposure to additional types of EMF is considered a possibility. This practice was most prevalent among workers involved in scanning animals.

Conclusion: The data illustrate recent trends and historical developments in magnetic resonance imaging and provide an extensive characterisation of the occupationally exposed population. A considerable number of workers are potentially exposed to MRI-related EMF. Type and frequency of potential exposure depend on the job performed, as well as the type of workplace.

1. Introduction

During the past decade, attention towards and debate about occupational exposure to electromagnetic fields (EMF) from magnetic resonance imaging (MRI) scanners has increased [1–4]. This was stimulated by the introduction of a proposal for a European directive on limiting occupational exposure to electromagnetic fields (EMF, 0–300 MHz) [5] in 2004. Various types of electromagnetic fields are used for magnetic resonance imaging: A static magnetic field (SMF, 0 Hz) which is constantly present inside and around an MRI scanner, radio-frequency (RF) pulses in the MHz frequency range that are used for signal generation, and switched gradient fields (SGF) in the kHz frequency range that are applied for spatial encoding [6,7]. Staff entering an MRI scanner room may experience instantaneous SMF exposure (measured as the flux density B_0, in Tesla), as well as time-varying magnetic field exposure (dB/dt, in Tesla per second) when they move through the non-uniform static magnetic field that surrounds a scanner. This field is also referred to as the stray field of the magnet or the static magnetic stray field. In some situations MRI staff are present inside the scanner room during image acquisition. Examples include certain MR-guided interventions, monitoring of anaesthetised patients, and guidance of anxious patients during the scan procedure [6]. Exposure to switched gradient fields can occur when one stands in close proximity to the scanner bore during image acquisition, and is dependent on field strength and slew rate, which varies per imaging sequence [8,9]. In order to be exposed to RF pulses one would have to be within close proximity to the RF coil during image acquisition, since the RF field intensity diminishes rapidly with increasing distance from the coil [6,10]. Occupational exposure to these RF fields is therefore uncommon, but might occur when an employee

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is being scanned voluntarily to test a new imaging protocol, or in the rare occasion when an employee lies in the scanner bore during the imaging process to support a patient.

Professional groups that might be exposed to MRI-related EMF include people using MRI for clinical diagnostics, MR-guided medical interventions on patients, clinical imaging of animals and for research purposes; but also people developing, testing or maintaining MR devices. It seems reasonable to assume that the explosive growth in the number of MRI units and the number of procedures performed since the early 1980s [11,12] has led to an increase in the number of people working with MRI. Furthermore, it can be assumed that the large increase in scanner magnet strength, resulting from technological advances in the field [13], has led to higher intensity of exposure among these workers. This endorses the need for exposure assessment. The drafting of a European Physical Agents Directive (EUPAD) [5] has led to much debate that has stimulated research on the topic of occupational MRI-related EMF exposure and health, including acute symptoms [2–4,6,8–10,14–19]. However, despite the increased attention there is, as yet, no clear insight into the number of individuals exposed and how exposure patterns differ between different job titles and workplaces. Within this context of increasing use of MRI and increasing field strengths, we performed an inventory among MRI departments within health care and research organisations throughout the Netherlands. This study was designed to (i) describe historical developments in the use of MRI within the Netherlands, (ii) assess the size and characteristics of the population that is currently occupationally exposed to MRI-related electromagnetic fields and (iii) identify variability in job and workplace characteristics that potentially affect this exposure (such as scanner type, magnet strength and specific procedures).

2. Materials and methods

2.1. Study population and data collection

Between September 2009 and March 2010, attempts were made to identify all health care and scientific research organisations within the Netherlands that owned at least one MRI scanner for *in vivo* imaging. The main resources for this exercise were online registers listing general, academic and specialised hospitals [20], private clinics and specialised treatment centres [21,22] and Dutch Universities [http://www.vsnu.nl/Universities/Research-universities.htm, accessed on 7 September 2009] officially registered in September 2009. This search was supplemented with an additional internet search and information from professional associations and people in the MR imaging field. Since the focus of this study is on MRI applications in health care and research settings, the survey did not include scanner manufacturing sites. In this paper, an MRI department is defined as 'any MRI department or MRI facility within an individual location of an organisation that employed one or more MRI scanners'. Thus, for organisations with multiple MRI-operating sites, each site was considered and approached as an individual MRI department.

From each identified MRI department, inquiries were made by e-mail or telephone about the number of MRI scanners they owned. Next, a contact person within each MRI department received a paper questionnaire that further queried the scanners in use, the number of scans performed, current applications and procedures, historical scanner use, the number of individuals working near the scanner(s), cleaning and maintenance procedures, and availability of safety protocols. If the questionnaire had not been returned after two e-mail reminders, the most pertinent questions from the questionnaire were administered by telephone interview. Contact persons were employees of the radiology department who were actively involved in the management or work practice of the radiology department in general or the MRI facility in particular. Most contact persons were MRI radiographers or coordinators of the MRI unit. Because of the diversity of topics addressed in the questionnaire, the contact persons were advised to consult colleagues for completion of the questionnaire. Where registered numbers on any questionnaire item were not available, respondents were requested to provide an estimate. Respondents were asked to report (i) the total number of individuals per job title working inside an MRI scanner room and (ii) the total number of individuals per job title working inside an MRI scanner room during image acquisition. Working inside a scanner room was used as proxy for exposure to B_0, while presence inside the scanner room during image acquisition was used as proxy for *potential* exposure to switched gradient fields and, to a lesser extent, RF fields.

2.2. Data handling and analysis

The MRI departments were grouped into five categories, based on their main application: Patient diagnostics, academic hospitals, human research, animal research, or animal diagnostics. Because academic hospitals performed patient diagnostics as well as human research, these were classified into a separate category. Some academic research departments performed both human and animal MRI scans; these were classified based on the most performed procedures. All data were analysed in SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

3. Results

We identified and approached 152 MRI departments (Table 1). Completed questionnaires were returned by 132 MRI departments (87%) while data on the most pertinent questions were collected via telephone interview from another 13 departments, resulting in an overall response of 95% (145 MRI departments). Most questionnaires were completed by an MRI radiographer (85%), sometimes in collaboration with colleagues. Of the identified MRI departments, 123 were categorised as patient diagnostics, 8 as academic hospital, 2 as human research, 6 as animal research and 6 as animal diagnostics department (see subscript Table 2).

The total number of scanners in operation was obtained from all 152 departments before sending out the questionnaires. A total of 227 MRI scanners were employed by the 152 identified departments. Of these, 205 devices were in use for human health care. Among the 145 departments that responded to the questionnaire or telephone interview, 217 scanners were in use. Only 3 per cent of these scanners had a magnet that was not permanently activated. These were mainly scanners with field strengths below 1 T. Forty-nine per cent of the MRI departments had ever made use of a mobile MRI scanner on at least one occasion, i.e. a portable MRI scanner that can be transported by road.

Table 2 presents an overview of the reported scanner properties per type of MRI department. The majority of human diagnostics and research facilities used horizontal cylindrical bore systems. Animal clinics, on the other hand, preferred the more spacious open scanners; probably because these are easier to use for patients of different sizes (i.e. different types of animals). MRI research on experimental animals was predominantly performed in small-bore systems, which were either horizontal MRI scanners specifically designed for this purpose, or vertical NMR scanners modified for mouse or rat imaging. The static magnetic field (B_0, expressed in Tesla; T) of the MRI systems varied between 0.2 and 17.6 T, with the majority of the scanners (59%) having a 1.5 T magnet. The highest field scanners (>3 T) were used exclusively by research departments and academic hospitals. This included two academic

Table 1
Identified clinical and research MRI departments in the Netherlands (2009–2010).

Type of organisation or institute in which the MRI department was embedded	Number of identified MRI departments	Response[a] (% of total population)
General hospital	102	100 (98%)
Academic hospital	8	7 (88%)
Academic children's hospital	1	1 (100%)
Specialised hospital	4	4 (100%)
Specialised treatment centre	20	17 (85%)
Animal clinic	6	6 (100%)
Research department, focus on human studies	3	2 (67%)
Research department, focus on animal studies	6	6 (100%)
Other[b]	2	2 (100%)
Total	**152**	**145 (95%)**

[a] Response to questionnaire (n = 132) or telephone interview (n = 13). To one MRI department of the 152 no questionnaire was sent, because the postal address was not available in time. For this department, a telephone interview was performed straight away.
[b] Other organisation/institute types include a local community health centre and a surgery facility within an academic hospital performing MR-guided neurosurgery and biopsies.

Table 2
Descriptive data of MRI facilities and MRI scanner properties in the Netherlands (2009–2010) per type of MRI department.

	Department type[a]					Total
	Patient diagnostics	Academic hospitals	Human research	Animal research	Animal diagnostics	
Number of scanners per MRI facility: count = number of departments (column%)						
1 scanner	86 (70%)	1 (13%)	1 (50%)	1 (17%)	6 (100%)	**95 (66%)**
2 scanners	33 (27%)	0 (0%)	1 (50%)	4 (67%)	0 (0%)	**38 (26%)**
>2 scanners	4 (3%)	7 (88%)	0 (0%)	1 (17%)	0 (0%)	**12 (8%)**
Distribution of system types: count = number of scanners (column%)						
Closed system (cylindrical bore)	154 (94%)	27 (84%)	3 (100%)	1 (8%)	1 (17%)	**186 (86%)**
Open system (transversal field)	6 (4%)	1 (3%)	0 (0%)	0 (0%)	5 (83%)	**12 (6%)**
Extremities scanner	1 (1%)	3 (9%)	0 (0%)	0 (0%)	0 (0%)	**4 (2%)**
Small bore animal scanner	0 (0%)	0 (0%)	0 (0%)	11 (92%)	0 (0%)	**11 (5%)**
Other[b]	3 (2%)	1 (3%)	0 (0%)	0 (0%)	0 (0%)	**4 (2%)**
Distribution of magnetic field flux density: count = number of scanners (column%)						
<1.0 T	10 (6%)	1 (3%)	0 (0%)	0 (0%)	6 (100%)	**17 (8%)**
1.0 T	37 (23%)	5 (16%)	0 (0%)	0 (0%)	0 (0%)	**42 (19%)**
1.5 T	109 (66%)	17 (53%)	1 (33%)	1 (8%)	0 (0%)	**128 (59%)**
3.0 T	8 (5%)	7 (22%)	2 (67%)	0 (0%)	0 (0%)	**17 (8%)**
$3 < x < 7$ T	0 (0%)	0 (0%)	0 (0%)	3 (25%)	0 (0%)	**3 (1%)**
7.0 T	0 (0%)	2 (6%)	0 (0%)	2 (17%)	0 (0%)	**4 (2%)**
>7.0 T	0 (0%)	0 (0%)	0 (0%)	6 (50%)	0 (0%)	**6 (3%)**

[a] MRI facilities are categorised in one of five department types, based on their main application:
-Patient diagnostics: general hospitals, specialised hospitals, treatment centres, local community health centre and surgery facility (n = 123).
-Academic hospitals: academic hospitals, academic children's hospital (n = 8).
-Human research: research departments with main focus on human studies (n = 2).
-Animal research: research departments with main focus on experimental animal studies (n = 6).
-Animal diagnostics: animal clinics (N = 6).
[b] Other system types include a mobile surgical MRI system for intra-operative MRI (neurosurgery facility), an MRI radiotherapy accelerator (academic hospital) and two open upright scanners (both at general hospital).

hospitals with a 7 T scanner, both of which were passively shielded. Of the scanners that were in use for human applications at the time of the survey, all of the older devices (purchased between 1991 and 2000) were 1 and 1.5 T scanners, with 1.5 T scanners becoming more popular in subsequent years. Since 2003 an increasing number of 3 T scanners have been installed and since the second half of the 2000s two 7 T scanners have been in use by academic hospitals. These data reveal a clear temporal trend in increasing field strengths, which is illustrated in Fig. 1.

Based on the survey, the total number of scan procedures in 2008 is estimated at approximately 682,000. Fig. 2 shows a strong temporal increase in the number of MRI procedures. This is paralleled by an increase in the number of organisations using MRI (data not shown), as well as an increase in the average yearly number of scan procedures per department (Fig. 3). Fig. 3 furthermore shows how the use of MRI has been integrated into different sectors over the years. In the early years (1981–early 1990s) MRI was only used at academic hospitals and at research institutes, for both patient diagnostics and research purposes. General (non-academic) hospitals started to adopt the diagnostic technique from the early 1990s, while the use of MRI as a diagnostic technique within animal clinics did not come into play until the early 2000s. Specific applications of magnetic resonance imaging, such as functional imaging (fMRI) and interventional MRI (iMRI), came into more regular use in the Netherlands from the first half of the 2000s (data not shown). By 2008, fMRI was being performed by 10% of the MRI

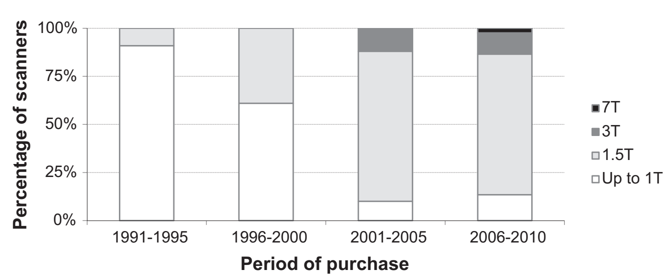

Fig. 1. Distribution of scanner magnet strength per period of purchase for MRI scanners that were in use at the time of data collection in human patient diagnostics and human research departments (n = 184 scanners).

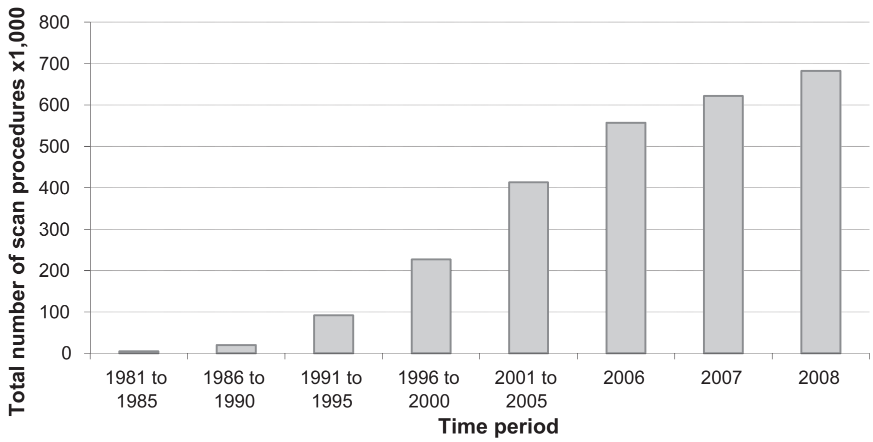

Fig. 2. Estimated yearly number of scan procedures in the Netherlands between 1981 and 2008. Averaged per five-year period, except for 2006–2008: reported per individual year. Estimates are based on extrapolation of non-missing data to the total number of 152 MRI departments by imputation of missing values. For 85–87% of the 152 departments it was known whether they were operating within the specified period, respectively. Depending on time period, 57–100% of those departments reported the number of performed scan procedures.

departments, while iMRI was employed by 6% of the departments. Fig. 4a presents the number of scan procedures performed per week at the different department types, showing high variability in scan activity. Differences in scan activity are also reflected in the number of days on which a scanner is in use (Fig. 4b). Sixty per cent of the scan procedures in academic hospitals were performed with contrast medium. In departments involved in other human diagnostics (23%), animal diagnostics (29%) and animal research (25%) this percentage was lower, and no contrast was administered in the two human research departments.

Persons identified to be working inside an MRI scanner room were classified into one of nine occupational groups, based on their job titles. Table 3 displays the number of workers per occupational group for two scenarios: firstly, working inside a scanner room and secondly, working inside a scanner room during image acquisition. The total number of individuals working inside an MRI scanner room within the Netherlands at the time of data collection is estimated at nearly 7000. Almost 3800 of these people (54%) worked inside a scanner room on a regular basis (i.e. on at least one day per month). Nine per cent of the total exposed population was regularly present inside a scanner room during image acquisition. Table 3 shows the numbers and frequencies of exposure per occupational group. The largest number of exposed workers is represented by radiographers (approximately 1700). Most of them (95%) worked in a scanner room on at least one day per week. Anaesthesiology staff performed tasks inside a scanner room on a less frequent basis, with 74% entering the room less than one day per month. However, 77% of anaesthesiology staff were reported to work inside the scanner room during image acquisition. A large proportion of radiographers (59%) and veterinary staff (61%) working inside a scanner room are also likely to be present during image acquisition; the latter group showing the highest frequencies. The percentages and frequencies in Table 3 are dominated by the patient diagnostics departments, which make up the largest group ($n = 123$ departments). However, which employees are exposed and how often this happens is partially determined by the type of MRI department at which they work. For example, a much higher proportion of staff at departments involved in scanning animals work inside a scanner room during image acquisition, than is the case for staff at human MRI facilities. Furthermore, higher frequencies of presence during image acquisition were reported for anaesthesiology staff at veterinary clinics in comparison to anaesthesiology staff at other workplaces. A full overview of numbers (potentially) exposed and exposure frequencies, stratified by department type, can be found in the online supplement.

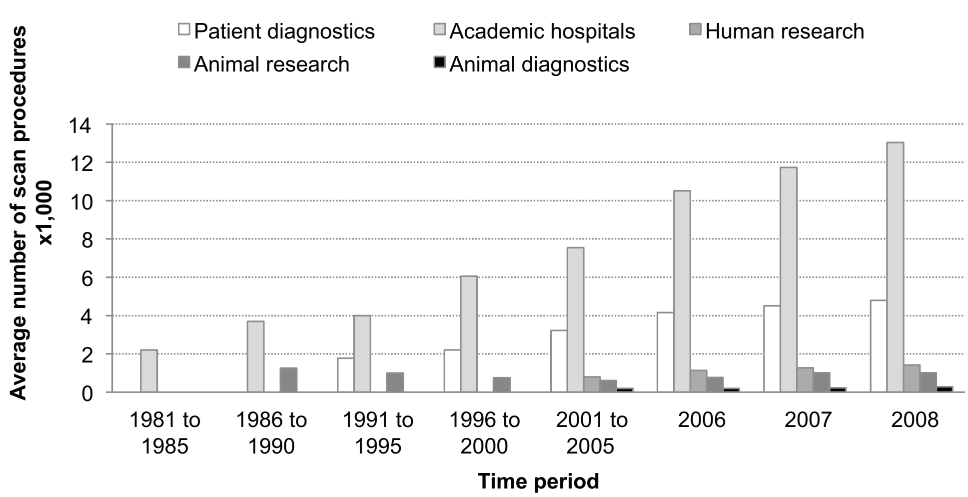

Fig. 3. Average yearly number of scan procedures per department between 1981 and 2008. Stratified by type of MRI department and averaged per five-year period, except for 2006–2008: reported per individual year.

Table 3
Estimated number of potentially exposed workers in the Netherlands (2009–2010).

	Estimated number of workers who work inside a scanner room[a]					Estimated number of workers who work inside a scanner room during image acquisition[a]			
	Total (*N*)	All freqs (% of total)	At least 1 d/mo (% of total)	At least 1 d/wk (% of total)	At least 3 d/wk (% of total)	All freqs (% of total)	At least 1 d/mo (% of total)	At least 1 d/wk (% of total)	At least 3 d/wk (% of total)
Radiographers	**1656**	100%	100.0%	95.5%	38.2%	58.8%	11.9%	4.0%	2.7%
Other radiology personnel[b]	**1123**	100%	56.9%	22.9%	10.3%	5.8%	1.7%	1.2%	0.0%
Anaesthesiology personnel[c]	**642**	100%	25.9%	1.7%	0.0%	77.3%	8.1%	7.5%	0.0%
Other medical personnel[d]	**2024**	100%	25.4%	9.1%	0.0%	46.5%	10.1%	6.9%	0.0%
Clinical physicists	**79**	100%	18.4%	9.8%	0.0%	9.2%	3.1%	0.0%	0.0%
Research staff[e]	**557**	100%	70.8%	43.6%	2.0%	20.5%	19.1%	9.9%	1.6%
Technical staff[f]	**601**	100%	19.8%	3.6%	1.8%	12.2%	1.3%	1.1%	0.9%
Cleaners	**258**	100%	90.4%	73.7%	60.8%	7.4%	2.3%	1.3%	0.0%
Veterinary and experimental animal staff[g]	**41**	100%	62.4%	33.0%	14.7%	60.7%	45.9%	33.0%	14.7%
Total[h]	**6981**	**100**%	**53.9**%	**35.9**%	**13.4**%	**38.9**%	**8.8**%	**5.0**%	**0.9**%

The questionnaire provided four frequency categories: 'on less than one day per month'; 'on less than one day per week'; 'on one to two days per week'; 'on three or more days per week'.
Freqs: frequencies; d/mo: day(s) per month; d/wk: day(s) per week.
[a] Estimates are based on extrapolation of available data to the total number of 152 MRI departments by imputation of missing values per job title. Data were available from 76% to 92% of the departments, depending on job title.
[b] Other radiology personnel: student radiographers, radiologists, radiology or radiography assistants.
[c] Anaesthesiology personnel: anaesthesiologists, anaesthesiology assistants, anaesthesiology nurses.
[d] Other medical personnel: nurses, medical doctors and medical specialists, doctors' assistants, supporting medical staff.
[e] Research staff: (postdoctoral) researchers, research assistants, PhD students, undergraduates.
[f] Technical staff: medical technicians, laboratory technicians, maintenance personnel.
[g] Veterinary and experimental animal staff: veterinarians, veterinary assistants, animal caretakers, experimental animal experts.
[h] One department reported 4 additional employees with unspecified job title. These were not included in the reported data.

Besides medical, technical and research personnel, more than 250 cleaners were reported to also perform tasks inside a scanner room. Their main activities were mopping the floor and emptying waste baskets. Cleaning of the MRI scanner itself may require people to be very close to or even inside the scanner bore, which can result in high levels of SMF exposure, especially at large-bore systems. At nearly all of the human diagnostics departments (96%) and academic hospitals (100%) the scanners were cleaned by radiographers. At research departments, the scanners were usually cleaned by technical or research staff, while at animal clinics this was often done by veterinary assistants. Differences appear in cleaning frequencies: MRI departments scanning human subjects cleaned their scanner(s) at variable intervals, the most reported frequency being once per week. Departments scanning animals cleaned their scanners with a higher frequency. At 50% of these departments the scanners were cleaned after each scan procedure.

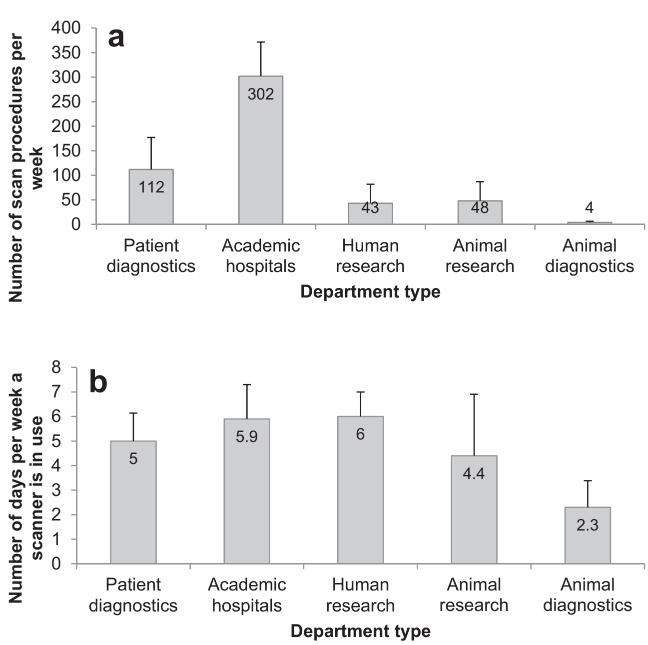

Fig. 4. (a) Average number of scan procedures performed per week per department, stratified by type of MRI department and (b) average number of days per week per department on which a scanner is in use, stratified by type of MRI department. Error bars show standard deviations.

At almost all (96%) of the MRI departments that performed scans on human subjects, workers regularly volunteered to be scanned on occasion, e.g. when a new scan protocol needed to be tested. This exposes them to all three types of MRI-related EMF. The frequency varied widely among MRI departments, ranging between one and 300 scans per year per department (mean = 12). The most reported jobs of people undergoing these voluntary scans were radiographers and student radiographers (reported by 96 and 49 per cent of the departments, respectively). Other jobs included other medical personnel, research staff, technical or maintenance staff and even administrative staff.

Among MRI departments scanning human patients and volunteers, presence of anaesthesiology staff inside the scanner room can be interpreted as an indication that scans were being performed on anaesthetised patients. This was the case for 100% of the academic hospitals and only 26% of the other clinical diagnostics departments. None of the human research departments scanned anaesthetised patients or volunteers.

4. Discussion

This paper presents the results of an inventory of MRI facilities in health care and research organisations that performed *in vivo* imaging on a regular basis in the Netherlands between 2009 and 2010. It provides numerical and graphical illustrations of recent trends and historical developments in the field of MR imaging. MRI usage varies considerably among countries. While the number of MRI procedures per capita in the Netherlands in 2008 was approximately half the number performed in Iceland, it was more than 1.5 times the number in Slovak Republic [11]. Regardless of the differences among countries, the world has seen a rapid increase in the use of magnetic resonance imaging and a move towards the use of higher scanner field strengths [11,13]. This trend has been clearly illustrated for the Netherlands by this survey. The increase in scanner field strength over the years suggests an increase in potential exposure intensity of MRI personnel from static magnetic stray fields. However, it should be noted that exposure to the static magnetic stray field around a scanner is not linearly related to the nominal strength of the magnet. It also depends on the distribution of the static magnetic stray field outside the scanner bore, which is determined by the design of the magnet, including its shielding. Active shielding of the static magnetic field might result in lower overall static magnetic field exposure (B_0) outside the scanner bore, but higher time-varying magnetic field exposure ($\mathrm{d}B/\mathrm{d}t$) when moving around close to the bore. The highest magnet strengths in the Netherlands were reported at experimental animal research departments, ranging from 4.7 to 17.6 T systems. These systems are mainly small-bore systems which are often well-shielded, especially the more recent models. The strongest magnets in large-bore systems were reported at academic hospitals and human research facilities. These facilities employed several actively shielded 3 T scanners and passively shielded 7 T scanners, the latter of which should result in high B_0 exposure. Although veterinary clinics used only low field scanners, most of these were open MRI systems. This design enables staff members to place their upper body into the space between the two magnets, where the flux density is at its peak – especially at the edges of the coils.

The increasing variety of MRI applications and workplaces that use MR imaging requires the expertise of individuals from a range of different occupational groups. The number of days that a person spends inside a scanner room varies considerably among jobs and type of MRI department. Among a working population of 8.7 million people in 2009–2010 [23], almost 7000 people worked near a healthcare or research MRI scanner and were thus highly probable of being exposed to SMF. Approximately 3800 of these people came inside an MRI scanner room on at least one day per month. The largest group in the Netherlands is represented by MR radiographers; almost 1700 radiographers worked with MRI. This is 29% of the estimated total population of diagnostic radiographers in the Netherlands [24]. More than 50% of the MR radiographers were reported to work in a scanner room on one or two days per week, which can probably be attributed to part-time work and the fact that many radiographers in the Netherlands work with other diagnostic modalities as well. These percentages may be different in countries where radiographers tend to specialise in one modality only. Cleaning personnel were found to be working inside a scanner room rather frequently (61% on at least three days per week). However, their daily exposure duration is expected to be low, since they only spend a few minutes inside a scanner room.

To our knowledge this study is the first to include an extensive characterisation of the occupationally exposed population in the health care and research sectors. This provides an indication of the degree to which various jobs are involved in magnetic resonance imaging. It is not known to what degree the observed patterns are representative of other European and non-European countries. Countries might differ with respect to job descriptions and work practices, as well as the proportion of MRI scans used for scientific research purposes and animal scanning. Similar studies in other countries would be informative.

The estimation of individual exposure levels was beyond the scope of this inventory, because this depends not only on workplace, scanner and scan procedures, but also on personal behaviour such as work pace, movement speed and distance from the scanner. Therefore, any work performed inside the scanner room was considered equally as a potential for static magnetic field exposure, without aiming to estimate exposure levels. Given the fact that most people working in a scanner room will have to perform tasks at the MRI scanner, we assume that entering a scanner room will equal a high probability of exposure to B_0. Therefore, in this study we consider presence inside a scanner room to be an appropriate proxy for exposure to static magnetic fields. For comparison of the various occupations involved in MR imaging (Table 3) the current study regarded only exposure frequencies. Exposure frequency data were reported as 'the average number of days on which an individual works inside an MRI scanner room', as well as 'the number of days on which one works inside an MRI scanner room during image acquisition'. Presence of a worker in a scanner room during image acquisition (i.e. during scanning) does not necessarily imply additional exposure to switched gradient fields (SGF) or radio frequency (RF) fields. This information can however be used as a proxy for *potential* exposure to these fields, mainly SGF. Exposure frequencies were assessed on day level. Thus, the number of days working inside a scanner room was regarded as an estimate of the number of days on which a person is exposed to a static magnetic field. It must be noted that this measure does not take into account how often or how long a person stays inside the scanner room during one day.

The results of our survey show how work practices differed per department type. The group of academic hospitals used scanners of higher field strengths, performed more scans on anaesthetised patients and did more scans involving contrast medium, when compared to other human imaging facilities. At departments involved in animal scanning a higher proportion of staff worked inside the scanner room during image acquisition, in comparison to human MRI facilities. These high numbers might be partially accounted for by the fact that our survey included three veterinary clinics and two animal research departments in which the control panel of the MRI scanner was in the same room as the scanner.

Given that very specific knowledge was required to answer some of the questionnaire items, the quality of the data can be sensitive to the know-how of the individuals who completed the questionnaire. Although respondents were advised to consult knowledgeable colleagues to complete items they could not answer, it is not known to what extent this actually happened.

Generally, an MRI facility is built in such a way that the stray field of the magnet drops to 0.5 mT within the walls of the scanner room. However, there may be cases where the design of the MRI facility allows for the 0.5 mT line to extend beyond the walls of the scanner room, into the control room, with the result that workers who do not enter the scanner room may be exposed to static magnetic stray fields just over 0.5 mT. This could potentially have resulted in an underestimation of the exposed population in our survey. Though we have no information about the extent to which this occurs, we suspect these cases are rare. However, the issue is of great importance for the screening of workers and patients who enter the control room, since the safety limit for interference with medical implants is set at 0.5 mT. Employers should ensure that areas where the field exceeds 0.5 mT be designated as 'controlled access areas' in accordance with IEC guideline 60601-2-33 [7]. In contrast to the potential underestimation of the exposed population as described above, the estimated size of the exposed population could be slightly overestimated because some employees (mainly radiographers) rotate their shifts at different locations within the same organisation. Hence there is the possibility of a few double counts since individual locations were targeted. Precisely to how many locations or employees this might apply is not known. The numbers of exposed workers are based on estimates by respondents, and thus do not represent officially registered numbers. With respect to other data, such as the number of MRI examinations performed per department, it is not known to what extent the reported numbers were based on registered information or on respondents' estimates. However, the reported numbers of MRI procedures in the Netherlands based on our survey are well in agreement with numbers reported by the National Institute for Public Health and the Environment (RIVM) [25] and the Organization for Economic Co-operation and Development (OECD) [11]. This supports the validity of the information provided through the questionnaires. Despite some weaknesses inherent to questionnaire studies, we believe that the high response rate (95%) and good agreement with independently collected MRI examination numbers reported by other resources enable us to provide a detailed, informative and representative overview of the potential for exposure to static magnetic fields from MRI scanners in The Netherlands.

5. Conclusions

The results of this survey show that both department type and occupation should be considered when identifying workplaces or target groups with a high potential for personal exposure to static magnetic fields or switched gradient fields. Personal exposure measurements should be performed to further characterise and quantify (variability in) occupational exposure levels, and to identify the role of exposure determinants in the MRI work environment. The results of the current inventory can facilitate the selection of target groups and workplaces for future exposure studies.

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Conflict of interest

The authors and their institution have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrad.2013.07.023.

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